

# Physics at $e^-e^-$ Colliders

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An overview of the physics motivations for  $e^-e^-$  colliders is presented.

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## 1. Introduction

The goal of this meeting is to encourage the exchange of new ideas about TeV-scale  $e^-e^-$  colliders, as well as their  $e^-\gamma$  and  $\gamma\gamma$  cousins. Such colliders are to be considered as a component of future linear collider programs along with the next generation of  $e^+e^-$  colliders. At first sight, the  $e^-e^-$  option might appear to require only trivial modifications of the  $e^+e^-$  mode. In fact, many interesting issues arise if one wants to optimize the  $e^-e^-$  performance to, for example, obtain luminosities comparable to those in the  $e^+e^-$  mode. These issues have been addressed previously<sup>1,2</sup> and will also be discussed at this meeting. Nevertheless, there is broad consensus that, with planning, the  $e^-e^-$  mode is a relatively simple, inexpensive, and straightforward addition to any linear collider program.

There are many thorny questions regarding when, where, and how such colliders should be funded and built — these issues are far beyond the scope of this talk. Rather, I will address a more modest (and much more intriguing) question: what novel and exciting possibilities for exploring weak scale physics will an  $e^-e^-$  collider provide?

## 2. New Physics

The standard model is now verified to extraordinary accuracy.<sup>3</sup> The strong, weak, and electromagnetic gauge couplings have been determined through numerous independent measurements and are known to 1 part in  $10^2$ ,  $10^3$ , and  $10^8$ , respectively. In the matter sector, there are now three complete generations with, for the most part, well-known masses and mixings. Even ten years ago, despite an intervening decade typically regarded as “quiet,” this story would have been far less complete. The contributions of the SLC, LEP, Tevatron, and HERA colliders at the high energy frontier have done an impressive job of bringing the present picture into sharp focus.

Sharp focus often leads to a greater appreciation of blemishes, however, and this is the case with the standard model. Some of the outstanding puzzles are the problems of

- *Electroweak Symmetry Breaking.* We do not understand the fundamental mechanism of electroweak symmetry breaking and the source of the gauge hierarchy, despite (or, better, as demonstrated by) the existence of many proposed solutions.
- *Flavor.* An explanation of the masses, mixings, and CP violation observed in the fermion sector remains a complete mystery, despite an abundance of data.
- *Gravity and Spacetime Structure.* Our understanding of gravity is limited, and the spacetime structure of our universe is open to wild speculation. It is remarkable that one can place two fingers slightly less than a millimeter apart and not know whether their interaction is primarily gravitational. The problem of the cosmological constant is emblematic of the lack of understanding in this area. It is tempting to speculate that, as we enter the 21st century, the

cosmological constant problem is a hint of fundamental change on the horizon, just as black body radiation was in the previous century. Certainly we should not exclude such a possibility.

Given all these mysteries, what are the lessons for future colliders? The standard approach is to examine the prospects for a given collider to probe a simple realization of one theoretical idea, and then another, and another, etc. Without actual data to guide us, this is probably the best we can do, and it will be the approach taken below. Before doing so, however, let us remind ourselves of the following caveats:

- *New physics may be complicated.* Studies of new physics typically consider some simple prototypes that are hoped to capture a few essential features. To give a concrete example, in supersymmetry, studies are often done in some minimal framework with few parameters. It is highly unlikely that such prototypes will be realized in nature. (It would also be truly disappointing if they were, as these prototypes are typically based on completely *ad hoc* assumptions, and the consistency of nature with such bland and unmotivated models would probably leave us at a loss for suggestive clues pointing toward further progress.)
- *New physics need not be modular.* It is an obvious possibility that several different types of new physics may reveal themselves simultaneously, considerably complicating their interpretation. One need only look at the last two chapters in the story of charged lepton discovery (the  $\mu$ - $\pi$  and  $\tau$ -charm puzzles) to find historical precedents. Again taking supersymmetry as an example, additional gauge bosons<sup>4</sup> and extended Higgs sectors are just some of the many possible extensions beyond the minimal supersymmetric standard model.
- *New physics need not appear in its entirety.* For example, in strongly coupled theories, only part of a resonance may appear, or in extra dimensional scenarios, perhaps only one Kaluza-Klein mode will be unveiled. Similarly, only a small fraction of the supersymmetric spectrum is required by naturalness to be at the weak scale.

Of course, it is possible that future colliders will discover only a standard model-like Higgs boson. It is also possible, however, that they may uncover so much anomalous data that it will be decades before a new synthesis is achieved. Given the number of fascinating fundamental questions remaining, some of which are intimately tied to the weak scale, I find the latter possibility far more likely.

### 3. Unique Features of $e^-e^-$ Colliders

If anything like the scenario just described is realized, it is clear that the future will require a flexible high energy physics program to make many model-independent measurements. With the LHC,  $e^+e^-$  colliders go a long way toward realizing this goal. Such colliders, with specifications

$$\sqrt{s} = 0.5 - 1.5 \text{ TeV}$$

$$\begin{aligned}\mathcal{L} &= 50 - 500 \text{ fb}^{-1}/\text{yr} \quad (1 \text{ R} = 10^4 - 10^5 \text{ events/yr}) \\ P_{e^-} &\equiv \frac{N_R - N_L}{N_R + N_L} \simeq 90\% \quad (\Delta P_{e^-} \lesssim 1\%),\end{aligned}\tag{1}$$

where  $P_{e^-}$  is the electron beam polarization, have been studied extensively. While their virtues and drawbacks can only be defined precisely on a case-by-case basis, it is possible to come to some general conclusions. The most salient virtues of  $e^+e^-$  colliders have been summarized by Murayama and Peskin<sup>5</sup> as

- *Holism.* At  $e^+e^-$  colliders, complete events yield more information than the sum of their parts. In other words, the well-specified initial energy and initial state  $e^+e^-_{L,R}$  yield important constraints.
- *Cleanliness.* Backgrounds are small, and may be reduced with beam polarization in many cases.
- *Democracy.* The  $e^+e^-$  initial state is electrically neutral and has no overall quantum numbers. Thus, both lepton and hadronic sectors may be explored with comparable statistics.

Following this rubric, let us now consider the properties of  $e^-e^-$  colliders:

- *Extreme Holism.* At  $e^-e^-$  colliders, the initial energy is again well known, but now the initial state may, in principle, be *exactly* specified by the possibility of highly polarizing both beams.
- *Extreme Cleanliness.* Backgrounds are typically extremely suppressed, and are even more readily reduced by the specification of both beam polarizations.
- *Dictatorship of Leptons.* Here  $e^-e^-$  and  $e^+e^-$  colliders differ sharply: in  $e^-e^-$  mode, the initial state has electric charge  $Q = -2$  and lepton number  $L = 2$ .

With respect to the first two properties, the  $e^-e^-$  collider takes the linear collider concept to its logical end. The third property makes  $e^-e^-$  colliders unsuitable as general purpose colliders, but, as we will see, it is also the source of many advantages.

## 4. Case Studies

There are many interesting opportunities for  $e^-e^-$ ,  $e^-\gamma$ , and  $\gamma\gamma$  colliders to probe new physics. I will highlight a few examples that illustrate the general remarks above.

### 4.1. Møller Scattering

The process  $e^-e^- \rightarrow e^-e^-$  is, of course, present in the standard model. At  $e^-e^-$  colliders, the ability to polarize both beams makes it possible to exploit this process fully.

For example, one can define two left-right asymmetries

$$\begin{aligned}A_{LR}^{(1)} &\equiv \frac{d\sigma_{LL} + d\sigma_{LR} - d\sigma_{RL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{LR} + d\sigma_{RL} + d\sigma_{RR}} \\ A_{LR}^{(2)} &\equiv \frac{d\sigma_{LL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{RR}},\end{aligned}\tag{2}$$

where  $d\sigma_{ij}$  is the differential cross section for  $e_i^- e_j^- \rightarrow e^- e^-$  scattering. There are four possible beam polarization configurations. Assume that the polarizations are flipped on small time intervals. The number of events in each of the four configurations,  $N_{ij}$ , depends on the two beam polarizations  $P_1$  and  $P_2$ . If one assumes the standard model value for  $A_{LR}^{(1)}$ , the values of  $N_{ij}$  allow one to simultaneously determine both  $P_1$  and  $P_2$  (and also  $A_{LR}^{(2)}$ ). For polarizations  $P_1 \simeq P_2 \simeq 90\%$ , integrated luminosity  $10 \text{ fb}^{-1}$ , and  $\sqrt{s} = 500 \text{ GeV}$ , Cuypers and Gambino have shown that the beam polarizations may be determined to  $\Delta P/P \approx 1\%$ .<sup>6</sup> Such a measurement is comparable to precisions achieved with Compton polarimetry, and has the advantage that it is a direct measurement of beam polarization at the interaction point.

Perhaps even more exciting, this analysis also yields a determination of  $A_{LR}^{(2)}$ , as noted above. Any inconsistency with the standard model prediction is then a signal of new physics. For example, one might consider the possibility of electron compositeness, parameterized by the dimension six operator  $\mathcal{L}_{\text{eff}} = \frac{2\pi}{\Lambda^2} \bar{e}_L \gamma^\mu e_L \bar{e}_L \gamma_\mu e_L$ . Barklow has shown that with  $\sqrt{s} = 1 \text{ TeV}$  and an  $82 \text{ fb}^{-1}$  event sample, an  $e^- e^-$  collider is sensitive to scales as high as  $\Lambda = 150 \text{ TeV}$ .<sup>7</sup> The analogous result using Bhabha scattering at  $e^+ e^-$  colliders with equivalent luminosity is roughly  $\Lambda = 100 \text{ TeV}$ .

#### 4.2. Bileptons

The peculiar initial state quantum numbers of  $e^- e^-$  colliders make them uniquely suited to exploring a variety of exotic phenomena. Chief among these are bileptons, particles with lepton number  $L = \pm 2$ . Such particles appear, for example, in models where the  $\text{SU}(2)_L$  gauge group is extended to  $\text{SU}(3)$ ,<sup>8</sup> and the Lagrangian contains the terms

$$\mathcal{L} \supset (\ell^- \quad \nu \quad \ell^+)_L^* \begin{pmatrix} & Y^{--} \\ Y^{++} & Y^+ \end{pmatrix} \begin{pmatrix} \ell^- \\ \nu \\ \ell^+ \end{pmatrix}_L, \quad (3)$$

where  $Y$  are new gauge bosons.  $Y^{--}$  may then be produced as an  $s$ -channel resonance at  $e^- e^-$  colliders, mediating background-free events like  $e^- e^- \rightarrow Y^{--} \rightarrow \mu^- \mu^-$ . Clearly the  $e^- e^-$  collider is ideally suited to such studies.

Bileptons are also obtained in models with extended Higgs sectors that contain doubly charged Higgs bosons  $H^{--}$ . The potential of  $e^- e^-$  colliders to probe resonances and other phenomena in these models has been reviewed by Gunion.<sup>9</sup>

#### 4.3. Supersymmetry

Supersymmetry would appear at first sight to be a perfect example of new physics that is difficult to explore at  $e^- e^-$  colliders. Indeed, the dictatorship of leptons forbids the production of most superpartners:  $e^- e^- \not\rightarrow \chi^0 \chi^0, \chi^- \chi^-, \tilde{q} \tilde{q}^*, \tilde{\nu} \tilde{\nu}^*$ .

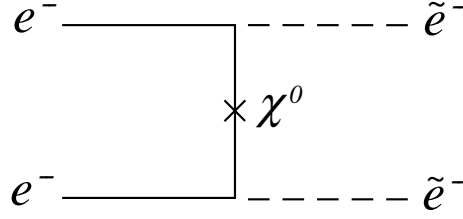


Fig. 1. Selectron pair production  $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^-$ , mediated by  $t$ -channel Majorana neutralino exchange.

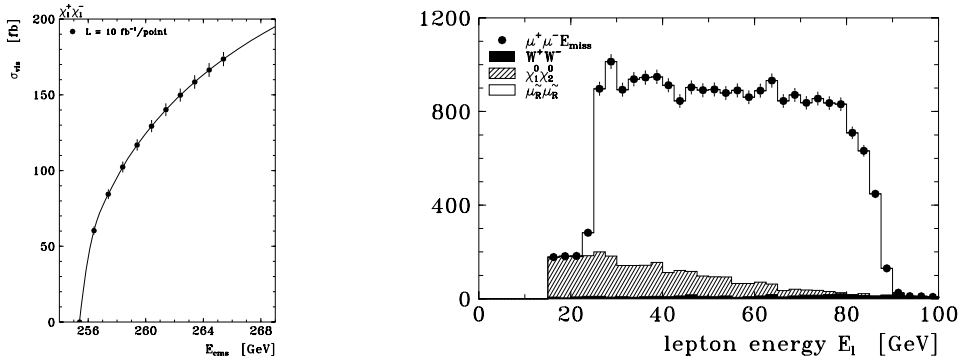


Fig. 2. Mass determination at  $e^+e^-$  colliders (a) for charginos via threshold scanning, and (b) for smuons via kinematic endpoints. (From the study of Martyn and Blair.<sup>13</sup>)

However, all supersymmetric models contain Majorana fermions that couple to electrons: the gauginos  $\tilde{B}$  and  $\tilde{W}$ . As was noted long ago by Keung and Littenberg,<sup>10</sup> these mediate selectron pair production through the process shown in Fig. 1.

Although supersymmetry at  $e^-e^-$  colliders is limited to slepton pair production, studies of slepton masses, mixings, and couplings can yield a great deal of information and provide excellent examples of how the properties of  $e^-e^-$  colliders may be exploited. Let us consider them in turn.

#### 4.3.1. Masses

Masses at linear colliders are most accurately determined through either kinematic endpoints<sup>11</sup> or threshold scans.<sup>12</sup> In a recent study of  $e^+e^-$  colliders, Martyn and Blair have considered both possibilities.<sup>13</sup> For the pair production of fermions such as charginos (see Fig. 2a), the cross section at threshold rises as  $\beta$ , the velocity of the produced particles. Threshold scans are then highly effective, and typical accuracies achieved are  $\Delta m \sim 10 - 100$  MeV. For the pair production of identical scalars, the cross section rises as  $\beta^3$  at threshold, and so threshold studies, though possible with very large luminosities,<sup>13</sup> are much less effective. Instead one turns to kinematic endpoints (see Fig. 2b), where mass measurements typically yield  $\Delta m \sim 0.1 - 1$  GeV.

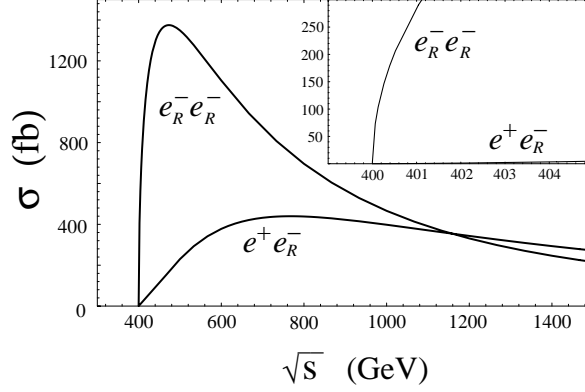


Fig. 3. Cross sections for selectron pair production at  $e^+e^-$  and  $e^-e^-$  colliders:  $\sigma(e_R^-e_R^- \rightarrow \tilde{e}_R^-\tilde{e}_R^-)$  and  $\sigma(e^+e_R^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-)$ .<sup>14</sup> The inset is a magnified view near threshold. Initial state radiation, beamstrahlung, and finite width effects are not included.

At  $e^-e^-$  colliders, however, the same-helicity selectron pair production cross section has a  $\beta$  dependence at threshold. This is easily understood: the initial state in  $e_R^-e_R^- \rightarrow \tilde{e}_R^-\tilde{e}_R^-$  has angular momentum  $J = 0$ , and so the selectrons may be produced in the  $S$  wave state. The unique quantum numbers of  $e^-e^-$  colliders therefore effectively convert a kinematic endpoint measurement into a threshold measurement (see Fig. 3), and extremely accurate scalar mass measurements are possible with minimal cost in luminosity. Incidentally, the full arsenal of linear collider modes allows one to extend this mass measurement to the rest of the first generation sleptons through a series of  $\beta$  threshold scans:  $e^-e^- \rightarrow \tilde{e}_R^-\tilde{e}_R^-$  yields  $m_{\tilde{e}_R}$ ;  $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_L^-$  yields  $m_{\tilde{e}_L}$ ;  $e^+e^- \rightarrow \chi^+\chi^-$  yields  $m_{\chi^\pm}$ ; and  $e^-\gamma \rightarrow \tilde{\nu}_e\chi^-$  yields  $m_{\tilde{\nu}_e}$ .

#### 4.3.2. Mixings

Now that neutrinos are known to mix, lepton flavor is no longer a sacred symmetry, and there is every reason to expect that sleptons also have generational mixings. Such mixing leads to decays  $\tilde{e} \rightarrow \mu\chi^0$  and may be searched for at either  $e^+e^-$  or  $e^-e^-$  colliders.

At  $e^+e^-$  colliders, the signal is  $e^+e^- \rightarrow e^\pm\mu^\mp\chi^0\chi^0$ . The backgrounds are

$$\begin{aligned}
e^+e^- &\rightarrow W^+W^- && \text{single } e_R^- \text{ polarization} \\
e^+e^- &\rightarrow \nu\nu W^+W^- && \text{single } e_R^- \text{ polarization} \\
e^+e^- &\rightarrow e^\pm\nu W^\mp \\
\gamma\gamma &\rightarrow W^+W^-
\end{aligned} \tag{4}$$

The first two backgrounds may be reduced by beam polarization, as indicated. However, the last two are irreducible.

In the  $e^-e^-$  case, the signal is  $e^-e^- \rightarrow e^-\mu^-\chi^0\chi^0$ . Possible backgrounds are

$$e^-e^- \rightarrow W^-W^- \quad \text{forbidden by total } L \text{ number}$$

$$\begin{array}{ll}
e^-e^- \rightarrow \nu\nu W^-W^- & \text{single } e_R^- \text{ polarization} \\
e^-e^- \rightarrow e^-\nu W^- & \text{double } e_R^- \text{ polarization} \\
\gamma\gamma \rightarrow W^+W^- & \text{same sign leptons}
\end{array} \tag{5}$$

In this case, all backgrounds may be eliminated, in the limit of perfect beam polarization. As a result, the sensitivity of  $e^-e^-$  colliders to slepton flavor violation is much greater than at  $e^+e^-$  colliders, and is also much more sensitive than current and near future low energy experiments.<sup>15</sup>

#### 4.3.3. Couplings

The excellent properties of  $e^-e^-$  colliders for exploring selectron production also make possible extremely precise determinations of selectron gauge couplings. Denoting the  $e\tilde{e}\tilde{B}$  and  $eeB^\mu$  couplings by  $h$  and  $g$  respectively, it is possible to verify  $h/g = 1$  to well below the percent level.<sup>16</sup> This then provides a quantitative check of supersymmetry and allows one to verify that the selectron is in fact the superpartner of the electron.

This measurement takes on additional importance if one notes that the relation  $h/g = 1$  is modified by heavy superpartners, and the deviation grows logarithmically with the superpartner mass scale<sup>17</sup> — that is,  $h/g - 1$  is a non-decoupling observable that receives contributions from arbitrarily heavy superpartners! Superheavy superpartners are phenomenologically attractive in many ways and may be present in a wide variety of models without sacrificing naturalness.<sup>18</sup> A measurement of  $h/g$  then provides one of the few probes of kinematically inaccessible superpartners and may help set the scale for far future colliders.

## 5. Conclusions

I have briefly reviewed the merits of  $e^-e^-$  colliders. The ability to highly polarize both beams and the unique quantum numbers of the initial state provide novel opportunities to study new physics.

A few illustrative examples were presented — of course, there are many more possibilities. I have taken the liberty of grossly oversimplifying matters by summarizing each theoretical talk at this conference with a single Feynman diagram (or, in exceptional cases, two). These are presented in Fig. 4. It is evident that the topics covered span a broad range, and include top quarks, Higgs bosons, extra gauge bosons, Majorana neutrino masses, strong  $WW$  scattering, and processes involving external and internal graviton states. Of course, to judge the effectiveness of  $e^-e^-$  colliders, it is important not just that  $e^-e^-$  colliders are sensitive to such physics, but that  $e^-e^-$  colliders provide probes at least as effective as or complementary to those available at the LHC,  $e^+e^-$  colliders, and low energy experiments, with reasonable experimental assumptions. Such important considerations will be addressed by the following speakers.

It is clear that in some scenarios, the unique properties of  $e^-e^-$  colliders will provide additional information through new channels and observables. While the

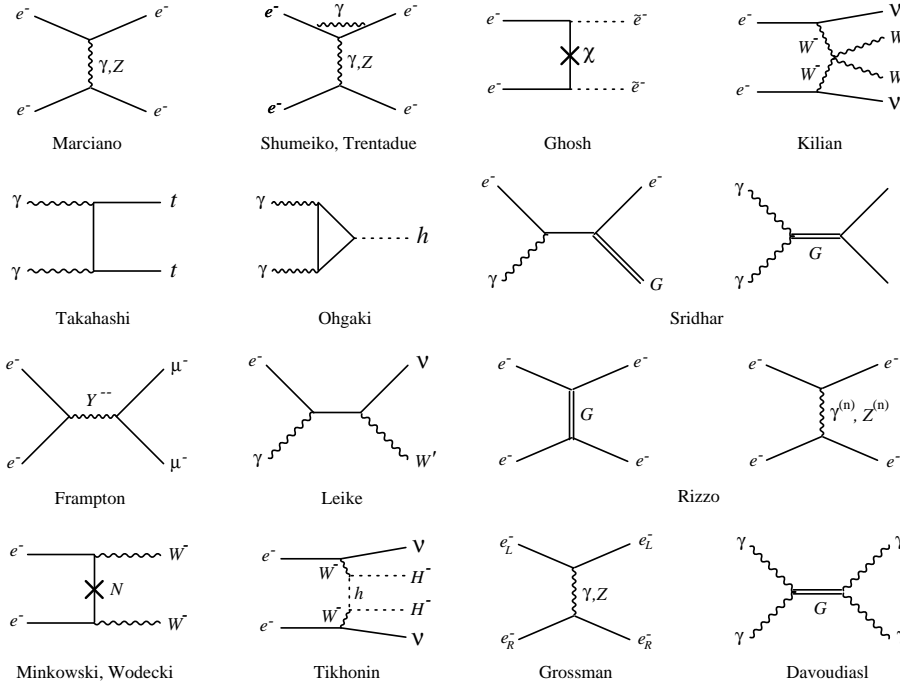


Fig. 4. Feynman diagram summary of talks presented at this conference.

specific scenario realized in nature is yet to be determined, given the exciting and possibly confusing era we are about to enter, such additional tools may prove extremely valuable in elucidating the physics of the weak scale and beyond.

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